Sequential Reactions Induced by Alpha Particles on ^{3}He[†]

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A prominent peak is observed in the forward-angle spectra of α particles if ^{3}He is bombarded by 63.7-, 71.7-, or 81.4-MeV α particles. The energy of the peak is consistent with a sequential decay process involving the 2.18-MeV state of ^{6}Li. At 71.7 MeV, proton spectra measured at backward angles show that the cross sections for formation of ^{6}Li* (2.18 MeV) agree with the intensity of the prominent α peak. The peak shape and position imply that the α particles are preferentially emitted forward with respect to the original ^{6}Li* direction. Two other peaks are observed in some of the α spectra, one of them possibly the result of a sequential decay involving ^{5}Li.

[NUCLEAR REACTIONS ^{3}He(α,α'), (α,p), $E = 63.7$, 71.7, 81.4 MeV; measured $\sigma(E,\theta)$.]

I. INTRODUCTION

Spectra of α particles emitted at forward angles from the bombardment of ^{3}He gas by 63.7-MeV α particles show a strong peak about 25 MeV below the elastic peak.[1] This peak was at first interpreted as inelastic scattering from a broad state in ^{3}He at about 20-MeV excitation,[1] apparently confirming the existence of a resonance in ^{3}He for which evidence had been found earlier in the radiative capture of deuterons by protons.[2] Additional measurements at bombarding energies of 71.7 and 81.4 MeV show a similar peak, but its energy corresponds to an apparent excitation of about 22.5 and 26 MeV, respectively. It was therefore concluded that the peak is not produced by inelastic scattering from ^{3}He, and a brief Erratum to this effect was published.[3]

The purpose of this paper is to amplify Ref. 3 and to present data on proton spectra measured at backward angles. These results indicate that a sequential decay process involving the first excited state of ^{6}Li is the most likely candidate for explaining the prominent peak.

II. EXPERIMENTAL DETAILS

The α spectra at 71.7 and 81.4 MeV were obtained with a scattering chamber and target cell different from those used in the 63.7-MeV experiment,[1] but the geometry was similar. The angular acceptance of the telescope was ±0.23°, defined by a front slit 0.76 mm wide, 26.4 cm from the center of the chamber, and a rear aperture 1.52 mm wide by 4.78 mm high, 54.4 cm from the center. The defining slits were made of 0.64-mm gold.

The telescope consisted of two silicon counters, a 292-μm ΔE counter and a 3-mm E counter, and was used for detecting reaction products emitted at forward angles. The $E+\Delta E$ energy scale was calibrated by observation of the elastically scattered α particles and recoil ^{3}He at several angles out to 38°.

The proton spectra at backward angles were ob-

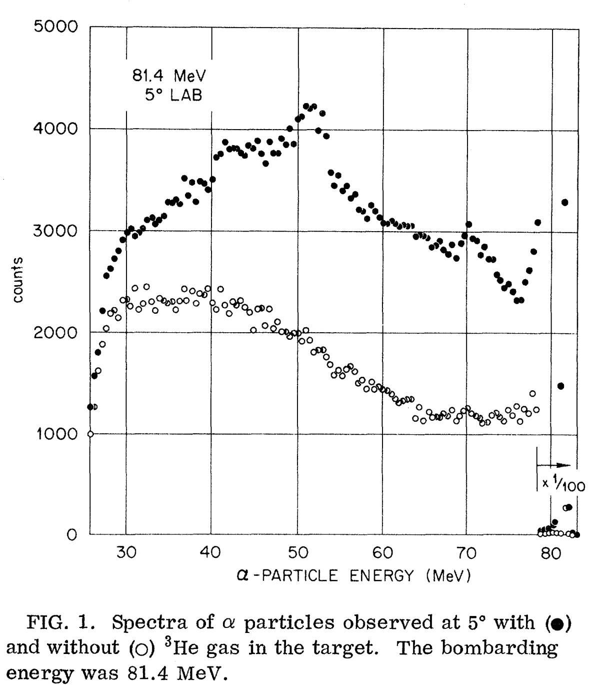

FIG. 1. Spectra of α particles observed at 5° with (●) and without (○) ^{3}He gas in the target. The bombarding energy was 81.4 MeV.

tained with a fully depleted 500-μm silicon detector about 21.6 cm from the center of the chamber. The polar acceptance angle was ±2.9°. No special method of particle identification was provided since, as will be shown later, none was necessary to pick out the proton groups of interest. The energy scale was calibrated by α particles from the decay of a ^{244}Cm source.

The gas cell, placed at the center of the scattering chamber, was a hollow cylinder about 18 cm in diameter with its axis perpendicular to the median plane of the chamber. It had a single slot, 1.9 cm high, covering a 240° angular range in the median plane. The ^{3}He gas, usually at a pressure of about 100 Torr, was contained by a 1.8-mg/cm^2 foil of type-H Kapton[4] glued to the outside of the cylinder.

The bombarding energies quoted in this paper have been corrected for energy loss in the entrance foil (~0.2 MeV). The energy scale for each spectrum was also corrected for energy loss in the gas-cell window. The uncertainty in beam energy was about ±0.1 MeV. In most of the spectra, the elastic peak was confined to about one channel, indicating that the over-all energy resolution was <0.4 MeV full width at half maximum (FWHM).

III. α SPECTRA

Figure 1 shows an example of an α spectrum at 81.4 MeV with and without ^{3}He gas in the target

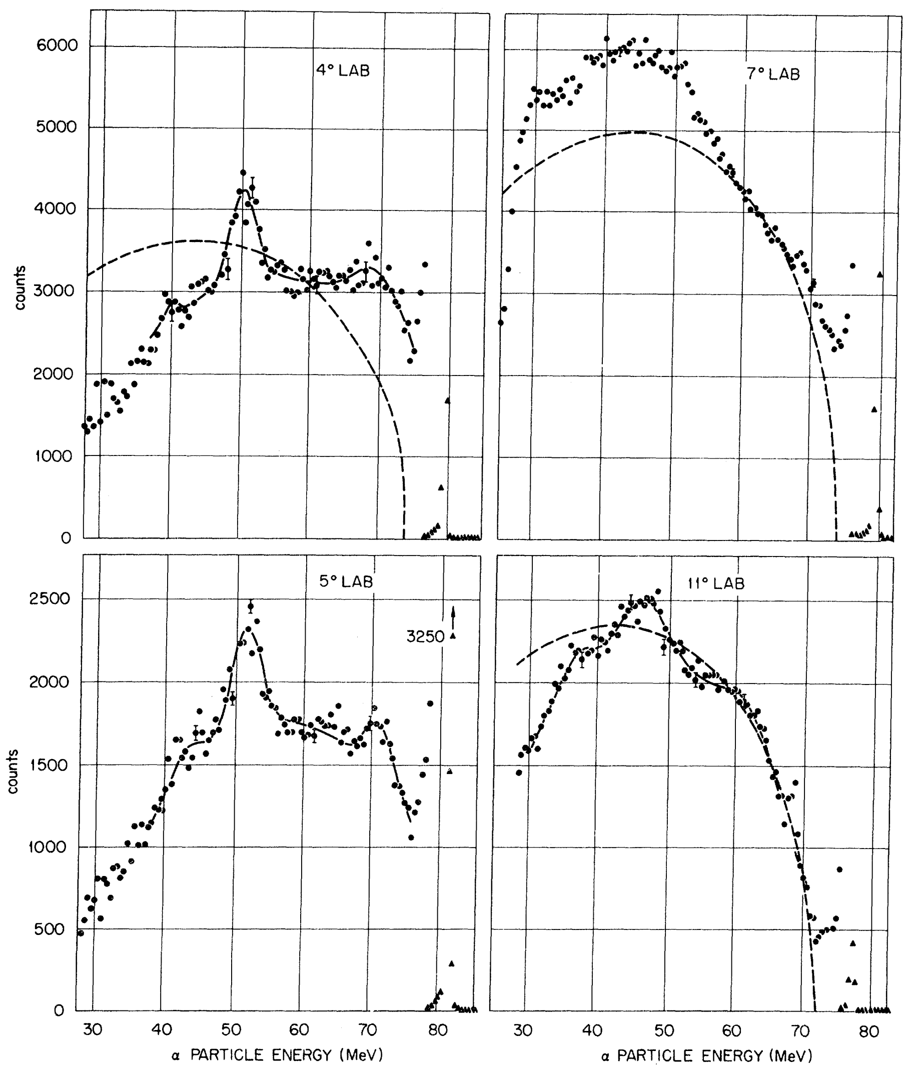

FIG. 2. Gas-in–gas-out difference spectra of α particles at 4, 5, 7, and 11° for a bombarding energy of 81.4 MeV. The points near 80 MeV were multiplied by $\frac{1}{100}$. The full curves are least-sqaures fits to three Gaussian peaks on a quadratic continuum. The dashed curves, arbitrarily normalized, show the phase-space distribution for breakup into three noninteracting particles.

cell. It is clear that there is a prominent α-particle peak due to the ^{3}He. The gas-out background, which is free of peaks in this energy region, decreases rapidly with angle; in the bombardments at 71.7 and 81.4 MeV it was not measured beyond 5°.

At 81.4 MeV, α spectra were obtained at 4, 5, 7, 9, and 11°. Figure 2 shows the gas-in–gas-out difference spectra for 4, 5, 7, and 11°. At 71.7 MeV, α spectra were obtained at these angles and also at 3.5, 13, and 15°. The gas-in–gas-out difference spectra at 71.7 MeV for 3.5, 4, and 5° appear in Fig. 3. Spectra at 63.7 MeV showing this peak for angles 4 to 13° appear in Ref. 1.

We will return in Sec. V to a detailed examination of the prominent α peak. Many of the spectra show evidence for two additional peaks; these will be discussed in Sec. VI.

IV. CROSS SECTIONS FOR ^{6}Li FORMATION

Consider the sequential process

$$\alpha + {}^3\text{He} \to p + {}^6\text{Li}^* \searrow \alpha + d\,. \qquad (1)$$

The first excited state of ^{6}Li (2.18 MeV) is unstable to $\alpha + d$ breakup, with a width of 25 keV. Since the ^{6}Li* kinetic energy is $\gtrsim$50 MeV under the conditions of these experiments, most of the decays occur far from the region of initial interaction.

The energy imparted to the α particle by the breakup is only 0.237 MeV. Consequently in the laboratory system these α particles are confined to a narrow cone about the initial direction of the ^{6}Li*; only forward-emitted ^{6}Li* nuclei can produce a forward-angle α peak via process (1). Measurement of the backward-emitted protons would determine the yield of the corresponding forward-emitted ^{6}Li* particles.

Accordingly, proton spectra were recorded for 11 angles from 121.4 to 170.2° at a bombarding energy of 71.7 MeV. Figure 4 shows two of these spectra. The strongest peak in each one is at the correct energy (about 5 MeV) for protons corresponding to ^{6}Li* (2.18 MeV), while the peak about 20 channels higher corresponds to the ground-state protons. The 2.18-MeV peak is clearly visible in all 11 spectra. At the three most forward

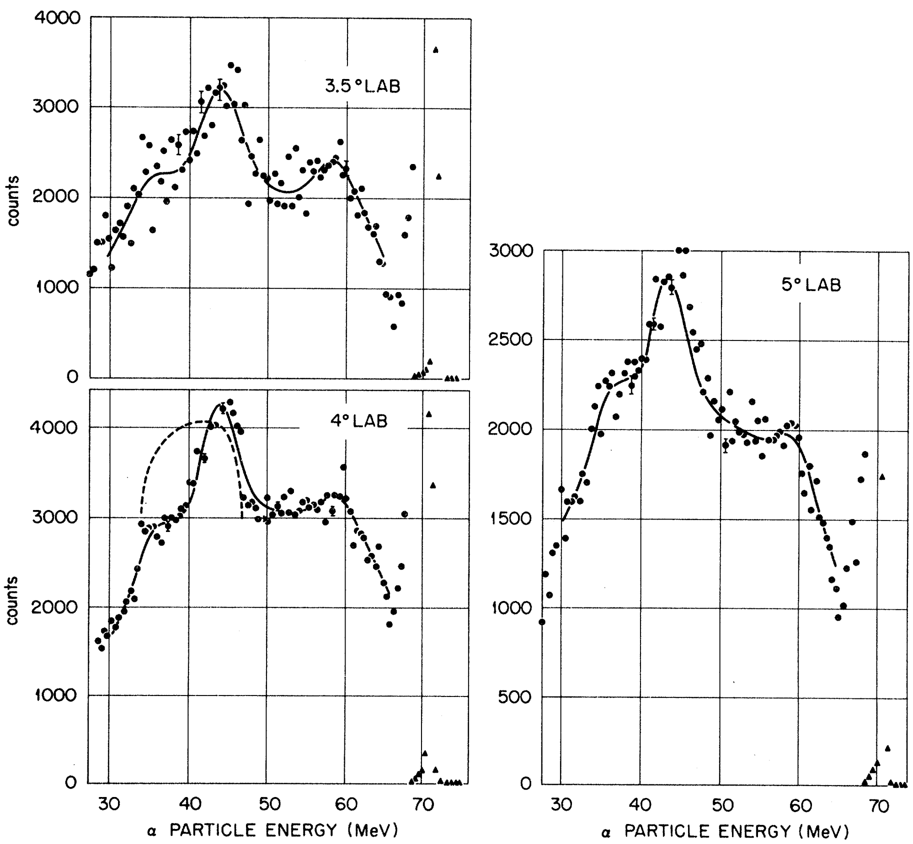

FIG. 3. Gas-in–gas-out difference spectra of α particles at 3.5, 4, and 5° for a bombarding energy of 71.7 MeV. The points near 70 MeV were multiplied by $\frac{1}{100}$. The curves are least-squares fits to three Gaussian peaks on a quadratic continuum. The dashed curve is the result of a calculation described in Sec. V.

proton angles (127.4, 124.6, and 121.4°), no useful ground-state data were obtained because the range of these protons exceeded the detector thickness. The 170.2° spectrum shows a weak group (at channel 80) corresponding to protons leaving ^{6}Li in its 3.56-MeV state. At angles forward of 152° this peak melts into the continuum.

The center-of-mass cross sections inferred from the proton spectra are shown by the open and closed circles in the left-hand side of Fig. 5 for the ground, 2.18-, and 3.56-MeV states. They are plotted as a function of the equivalent ^{6}Li center-of-mass angle for greater clarity in the discussion that follows.

The ground state of ^{6}Li is particle-stable and the 3.56-MeV state is known to decay only by γ emission. At forward angles, lithium particles corresponding to both of these states were identified with the ΔE, E telescope. The cross sections derived from the ^{6}Li observations are shown by the triangles in Fig. 5. These results are in satisfactory agreement with those from the proton yields.

The diamonds in Fig. 5 show ^{6}Li* (2.18-MeV) cross sections calculated from the area of the prominent α peak at laboratory angles of 3.5, 4, 5, and 7° on the hypothesis that the α particles come from breakup of this state.[5] These results

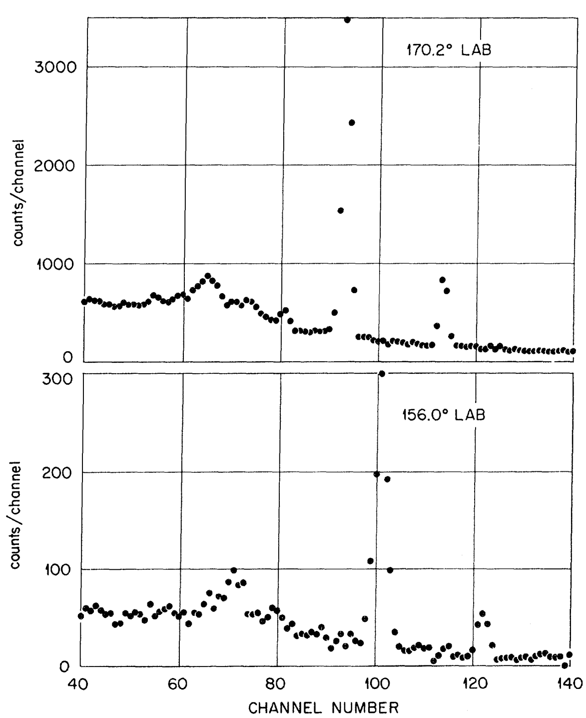

FIG. 4. Backward-angle spectra at 71.7 MeV. The upper spectrum was obtained with 4 times as much integrated beam as the lower one.

are in satisfactory agreement with the proton yields. We conclude that (at least for 71.7 MeV) the $\alpha+d$ fragmentation of ^{6}Li* (2.18 MeV) provides sufficient numbers of α particles to account completely for the intensity of the prominent peak.

The 81.4-MeV telescope data at forward angles also included ^{6}Li groups corresponding to the ground state and 3.56-MeV state. The cross sections inferred from these data are indicated by triangles on the right side of Fig. 5. Also shown are diamonds representing the ^{6}Li* (2.18-MeV) cross section, again obtained from the α yield in the main peak. The cross sections for each group at this energy are about 30% lower than those at 71.7 MeV; the angular distributions are very similar.

V. CHARACTERISTICS OF THE MAIN PEAK

In the α spectra at 63.7 MeV,[1] the main peak is easily seen at angles as large as 11°. For the higher beam energies it is weaker and cannot be seen at all at some angles.

A least-squares peak-fitting procedure was applied to all the spectra. As pointed out earlier, some of the spectra show two additional peaks. For simplicity, the three peaks were represented by Gaussians and the underlying continuum by a quadratic. This procedure converged satisfactorily for all of the spectra having peaks obvious to the eye. In some spectra (the 81.4-MeV spectrum at 7°, Fig. 2, and all the spectra not shown), the peaks were very weak or absent, and the least-squares procedure did not produce statistically reliable area determinations.

The main-peak areas that appeared to be trustworthy were used to calculate the laboratory cross sections shown in Table I. Results from the 63.7-MeV data are included for completeness. The decrease of intensity of the main peak with increasing angle and beam energy is clear. To

TABLE I. Laboratory cross sections in mb/sr for the main α peak.

Lab angle	Beam energy in MeV		
	63.7 [a]	71.7	81.4
3.5°	···	390	···
4°	210	146	92
5°	163	97	78
6°	146	···	···
7°	100	59	···
8°	87	···	···
9°	23	···	···
11°	22	···	29
13°	9	···	···

[a] Data from Ref. 1.

convert these results to c.m. cross sections for formation of ^{6}Li* (2.18 MeV), as was done to produce the diamonds in Fig. 5, the laboratory cross sections should be divided by a factor of 17 to 21, the exact number depending on angle and energy. All results in the table are uncertain by about ±10% because of systematic effects involving errors in geometry, beam integration, and the like. The cross sections are subject to an additional uncertainty due to the arbitrary choice of peak and continuum shapes, which in unfavorable cases might be appreciably greater than 10%.

Some of the α particles from ^{6}Li* breakup may enter the telescope together with the associated deuteron. The resulting pileup pulse would appear far from the α-particle locus of the ΔE, $E+\Delta E$ data array. An examination of the data array showed that the number of events possibly due to pileup was well below 0.01% of the main-peak intensity, in agreement with estimates based on the geometry.

The position and shape of the peak are determined by details of the reaction and subsequent breakup. The α energies corresponding to θ', the angle of emission of the α in the ^{6}Li* c.m. system measured from the original ^{6}Li* velocity, of 0 and 180° are shown by the full lines in Fig. 6. For a given angle of observation, the maximum and minimum α energies are somewhat outside the values for $\theta'=0$ and 180°. The effect is no more than a few tenths of an MeV for angles up to 5°, but increases with angle. For example, at 63.7 MeV, the $\theta'=0°$ energy for α particles observed at 15° is 32.4 MeV while the maximum calculated energy is 34.9 MeV; the latter corresponds to emission of ^{6}Li* at about 12° to the beam direction followed by breakup with $\theta'\sim 40°$. The dashed lines in Fig. 6 just above the $\theta'=0°$ curves show these maximum energies. A more complete picture of the limiting α energies is given by the dashed lines in the 63.7-MeV portion of Fig. 6. Note that the kinematic relations have a second branch for ^{6}Li* angles <12°, corresponding to forward emission of the proton in the first step of process (1).

The main-peak centroids and widths (FWHM) from the least-squares fits are shown by the full points and flags in Fig. 6. We now ask, what values of θ' may be inferred from the observed centroid energies? Kinematics does not lead to a

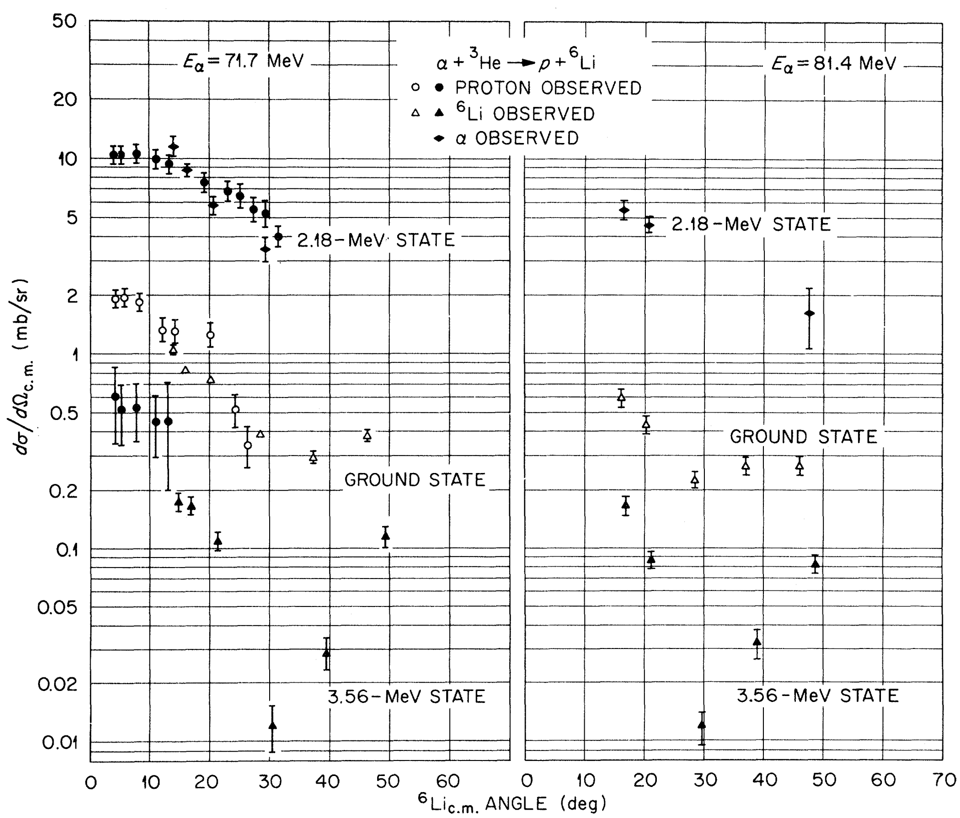

FIG. 5. Cross sections for exciting various states of ^{6}Li, as obtained from observation of protons (○,●), ^{6}Li (△,▲), and α particles (◆). The open points designate the ground-state data.

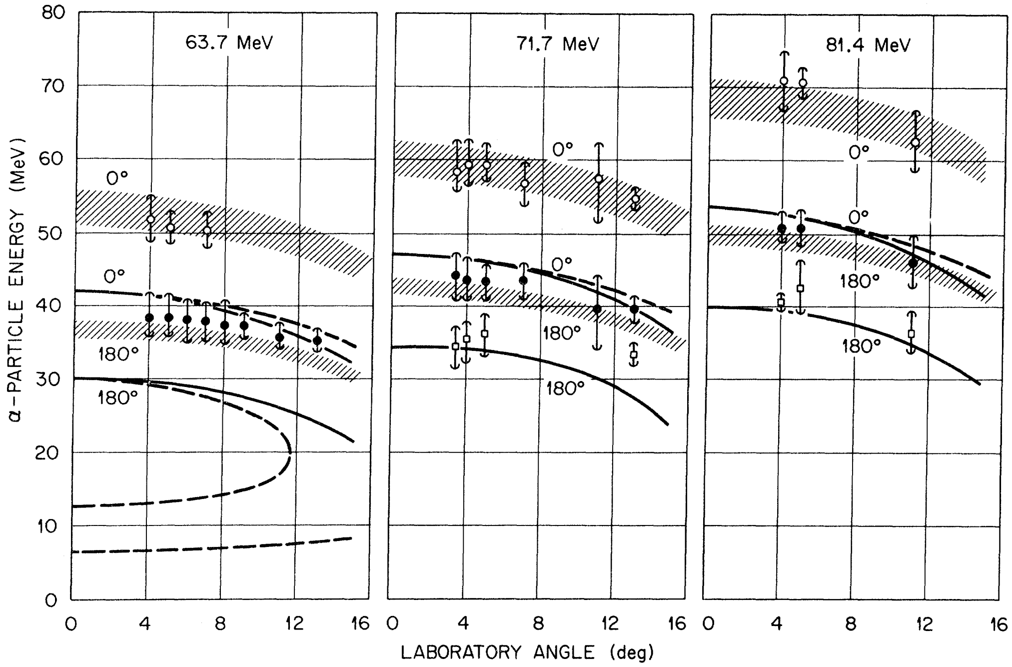

FIG. 6. α-particle energies as a function of angle for three bombarding energies. The full points and their flags represent experimental centroid energies and widths (FWHM) of the prominent α peak at angles where it was clearly discerned. The open points show the centroids and widths for the two minor peaks. The curves (full and dashed) show limiting situations of kinematics for the $p+{}^6$Li* (2.18-MeV) reaction, while the shaded areas are for $d+{}^5$Li (g.s.). These curves and shaded areas are described in the text.

unique answer because the original ^{6}Li* direction is unknown. However, we find that the centroids always correspond to θ' in the range from 0 to about 60°. There are practically no particles in the main peak with energies corresponding to $\theta' \sim 90°$. As mentioned in the next section, there is evidence for α particles at energies corresponding to emission at θ' near 180°, but this group is weaker than the main peak.

A nonuniform c.m. angular distribution is also exhibited in the sharpness of the observed peaks. As an example, a calculation of the peak shape for α particles observed at 4° was made in which it was assumed that in the c.m. system the α particles were emitted uniformly in solid angle. This distribution was transformed to the laboratory system with weighting of the ^{6}Li* (2.18-MeV) intensity according to the proton data of Fig. 5. The result, arbitrarily normalized, is shown by the dashed curve in the 4° spectrum of Fig. 3, positioned on a base line of about 3000 counts/channel. The calculated peak is much flatter than the observed peak and is about twice as wide.

We conclude that forward emission of the α particles from the ^{6}Li* breakup is favored.

In some spectra a small fraction of the α particles in the main peak have an energy greater than the maximum possible for breakup of ^{6}Li* (2.18 MeV). Higher-energy α particles can arise from sequential decay via higher excited states of ^{6}Li; the proton spectra of Fig. 4 show evidence for formation of such states.

VI. OTHER α-PARTICLE PEAKS

Many of the spectra show evidence for one peak above and one below the prominent one. Figures 2 and 3 show least-squares fits to sums of three peaks on a smooth continuum. The open points in Fig. 6 show the centroids and widths of these additional peaks for all angles at which statistically reliable values for these quantities were found. The areas of these additional peaks were not well-determined, but were generally between $\frac{1}{5}$ and $\frac{1}{2}$ of the main-peak intensity.

The lowest peak has an energy that is consistent with backward emission of α particles from breakup of ^{6}Li* (2.18 MeV). This peak is absent from the 63.7-MeV data because of an instrumental cutoff.

To find a plausible explanation for the highest peak we must consider other processes that can give rise to α particles. The following sequential decays are possible in addition to process (1):

$$\alpha + {}^3\text{He} \to d + {}^5\text{Li} \searrow \alpha + p\,, \quad (2)$$

$$\alpha + {}^3\text{He} \to n + {}^6\text{Be} \searrow \alpha + 2p\,, \quad (3)$$

$$\alpha + {}^3\text{He} \to p + n + {}^5\text{Li} \searrow \alpha + p\,, \quad (4)$$

$$\alpha + {}^3\text{He} \to p + p + {}^5\text{He} \searrow \alpha + n. \quad (5)$$

Simultaneous breakup is also possible, into three final-state particles

$$\alpha + {}^3\text{He} \to \alpha + p + d \quad (6)$$

or four final-state particles

$$\alpha + {}^3\text{He} \to \alpha + p + p + n. \quad (7)$$

Let us first dispose of (6) and (7). If there are no interactions among the particles in the final state, the α spectra should be characterized by the appropriate phase-space distribution without sharp structure. As shown in Fig. 2, three-body phase space matches the underlying continuum rather poorly. Four-body phase space, which would be appropriate for (7), rises even more steeply and the fit would be worse. Unsatisfactory fits were also obtained for other spectra showing no peaks. We conclude that simultaneous breakup without interactions among the final-state particles by itself does not account for the shape of the underlying continuum.

We return to consideration of the peaks. Processes (4) and (5) are not expected to give a well-defined α peak since the precursor of the α particle in each case comes from a three-body breakup and thus may have any energy over a wide range.

Process (3) is difficult to characterize simply because the ^{6}Be nucleus breaks up into three particles. If the two protons are emitted as a diproton, the possible α energies are similar to those for process (1) (shown by curves in Fig. 6), except that they are approximately 5–10% lower. Thus forward c.m. emission of the α particle with both protons going backward can contribute to the main peak. However this contribution should be small since the ground state of ^{6}Be is an isobaric analog of the 3.56-MeV state of ^{6}Li, and (as shown in Fig. 5) the latter is formed with about $\frac{1}{20}$ the intensity of the 2.18-MeV state. This expectation is in agreement with a fact already noted, that the 2.18-MeV cross section is sufficient to account for all the α particles in the main peak.

Another limiting case for the ^{6}Be breakup occurs when the protons go off in opposite directions in the c.m. system, leaving the α particle at rest. In the laboratory system this transforms to an α particle moving forward with an energy almost midway between the limiting cases of the previous paragraph. The α energies from all other ^{6}Be decays are also between these values. We conclude that the ^{6}Be breakup cannot be responsible for the highest peak.

We are left with only process (2) to account for the highest peak. The ground state of ^{5}Li may contribute since it is particle unstable. Its width is about 1.5 MeV; the shaded regions of Fig. 6 show the range of α-particle energies corresponding to this width for breakup angles of 0 and 180°. (As was true of the ^{6}Li* breakup, the 0 and 180° loci do not correspond strictly to the maximum and minimum energies. However, the difference here is smaller; even at 15° the maximum energy is only 2.5% higher than the 0° energy.) Figure 6 shows that the energy of the highest peak is generally consistent with forward emission of α particles from the ground-state breakup of ^{5}Li.

The 4 and 5° points at 81.4 MeV appear at an energy that is somewhat too high. Decay via an excited state of ^{5}Li can give α particles of higher energy. The first excited state of ^{5}Li is very broad ($\Gamma \sim 3-5$ MeV) and may not give rise to a well-defined peak. On the other hand, the second excited state (16.65 MeV) is fairly sharp. Decay of this state can produce 4° α particles as high as 74.4 MeV, even without allowance for its width ($\Gamma \approx 0.3$ MeV).

It may be noted that the main α peak has the correct energy for backward emission from the ^{5}Li ground state, although as pointed out above, its intensity can be completely accounted for by forward breakup of ^{6}Li* (2.18 MeV). Direct observation of the backward deuterons from (2) would have been interesting. Unfortunately, those emitted at angles beyond 125° have insufficient energy to penetrate the window of the gas cell.

VII. OTHER EXPERIMENTS

α spectra from the bombardment of ^{3}He by 42-MeV α particles were published by Warner, Vincent, and Boschitz[6] at 17.5, 20, 22, and 25°. A small yet distinct bump appears at about 20 MeV in their 17.5° spectrum; a hint of one occurs near 16 MeV in their 20° data. Neither bump has been satisfactorily accounted for. The corrected[7] peak energies at both angles are too high to have been due to process (1), but are within the range possible for process (2). Again the observed bumps are narrower than the full energy range and correspond to preferentially forward emission of the α particles from ^{5}Li.

Recent work[8] with 115-MeV α particles on ^{3}He failed to reveal any peaks from 4 to 8°. This is at least qualitatively consistent with our observation that the peaks become increasingly difficult to see as the bombarding energy increases.

ACKNOWLEDGMENTS

The possibility that the main peak might be due to sequential decay via ^{6}Li* (2.18 MeV) was suggested by M. J. Saltmarsh and R. E. Brown independently. We wish to thank them for their interest and for the calculations they performed related to this problem. We are indebted to C. C. Chang for bringing to our attention the process involving the 16.65-MeV state of ^{5}Li, and to W. W. Eidson for suggesting the $d+\alpha$ pileup process. We thank W. Meyerhof and R. van Dantzig and coworkers for useful discussions. The peak-fitting analysis was ably carried out by R. F. Nelson, an Oak Ridge Associated Universities summer trainee from Iowa State University, Ames. Part of this manuscript was prepared while the first author was on temporary assignment at the Brookhaven National Laboratory Tandem Van de Graaff Facility; we express our thanks for their assistance.

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[3]M. L. Halbert and A. van der Woude, Phys. Rev. Lett. 26, 1679 (1971).

[4]Kapton is DuPont's trade name for its polyimide film. This material is remarkable for its resistance to damage by a charged-particle beam. We wish to thank R. E. Brown for supplying us with a sample.

[5]It was assumed here that the breakup α particles observed at a given laboratory angle came from ^{6}Li* emitted at the same angle. Actually this is not so—the half angle of the breakup cone is about 5°. But since the ^{6}Li* production cross section is monotonic and does not vary substantially over a 5° range, it is probably safe to characterize the α yield at a given angle as the average yield of ^{6}Li* emitted at the same angle.

[6]R. E. Warner, J. S. Vincent, and E. T. Boschitz, Phys. Lett. 24B, 91 (1967).

[7]We applied a correction to the observed energies to account for energy losses in foils, our inexact knowledge of the beam energy, and other experimental details not stated by the authors of Ref. 6. This correction was inferred from the inelastic markers shown in their published spectra.

[8]P. E. Frisbee and H. G. Pugh, Nucl. Phys. A191, 658 (1972).